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Search for radio emission from the exoplanets Qatar-1b and WASP-80b near 150 MHz using the Giant Metrewave Radio Telescope

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ABSTRACT

We present radio observations made towards the exoplanets Qatar-1b and WASP-80b near 150 MHz with the Giant Meterwave Radio Telescope. These targets are relatively nearby irradiated giant exoplanets, a hot Jupiter and a hot Saturn, with sizes comparable to Jupiter but different masses and lower densities. Both the targets are expected to host extended H/He envelopes like Jupiter, with comparable or larger magnetic moments. No radio emission was detected from these exoplanets, with 3σ limits of 5.9 and 5.2 mJy for Qatar-1b and WASP-80b, respectively, from these targeted observations. These are considerably deeper limits than those available for exoplanets from wide field surveys at similar frequencies. We also present archival VLA observations of a previously reported radio source close to Vir 61 (which has three exoplanets). The VLA observations resolve the source, which we identify as an extragalactic radio source, i.e. a chance association with Vir 61. Additionally, we cross-match a recent exoplanet catalogue with the TIFR GMRT Sky Survey ADR1 radio catalogue, but do not find any convincing associations.

Key words: radio continuum: planetary systems – planets and satellites: individual: Qatar-1b – planets and satellites: individual: WASP-80b

1 INTRODUCTION

Thousands of exoplanets are known today and transit surveys are expected to detect thousands more in the near future. The exoplanets detected to date span a diverse range of orbital and bulk properties and host stars. We are now entering a new era where detailed observations are characterising their atmospheric processes and chemical compositions (e.g. Deming & Seager 2017; Kreidberg 2018; Madhusudhan 2019), from observations made at ultraviolet to infrared wavelengths. Any detection of radio emission from exoplanets would present a unique opportunity to characterise their magnetic processes and internal structures which are inaccessible from other observations. Solar system planets span diverse intrinsic magnetic field strengths, from 0.2 G in the ice giants, through 0.5 G in the Earth, to 4.2 G in Jupiter, suggesting the presence of dynamos in their convective interiors (Stevenson 2003). Theoretical studies have predicted that cyclotron radio emission from giant exoplanets with magnetic field strengths comparable to Jupiter's are potentially observable with existing and upcoming radio facilities (e.g. Lazio et al. 2004; Grießmeier et al. 2007; Zarka et al. 2001; Zarka 2007). For close-in giant exoplanets, the dominant source of energetic electrons interacting with the planetary magnetic field is generally the stellar wind (e.g. Zarka 2007), but the effect of auroral processes and potential exomoons have also been investigated (e.g. Nichols 2011, 2012; Noyola et al. 2014).

The gyrofrequency ($f_{\rm cy}$) for the electron–cyclotron maser radiation due to a planetary magnetic field ($B_{\rm p}$) is given by $f_{\rm cy} = 2.8(B_{\rm p}/1\ {\rm G})$ MHz, implying that emission from exoplanets with $B_{\rm p} \sim 1$–100 G can be detected in the frequency range of 2.8–280 MHz. For Jupiter, the observed radio frequency cut-off in its cyclotron emission leads to an estimated maximum $B_{\rm p}$ of 14 G. While future facilities such as the Square Kilometre Array (SKA) will be able to detect Jovian and sub-Jovian magnetic fields, exoplanets with $B_{\rm p}$ of a few times the Jovian value (e.g. ~ 50 G), i.e. $f_{\rm cy} \sim 150$ MHz, are already within the frequency regime of current facilities.

Here we present a search near 150 MHz for radio emission from two exoplanets with the Giant Metrewave Radio Telescope (GMRT). Previous radio searches for exoplanets at similar frequencies are discussed briefly in Section 2, and the selection of our targets is presented in Section 3. The GMRT observations and the data reduction are described in Section 4 along with the results and conclusions.

2 PREVIOUS SEARCHES

Sirothia et al. (2014) searched for radio emission from 175 exoplanets at 150 MHz from the TIFR GMRT Sky Survey (TGSS), which has a resolution of about 20 arcsec. They did not find evidence of radio emission associated with their targets, and obtained 3σ upper limits of between 8.7 and 136 mJy. Sirothia et al. did note that there was an elongated (about 1 arcmin) radio source at 150 MHz close to 61 Vir, which has three identified exoplanets (Vogt et al. 2010). This radio source is also seen Northern VLA Sky Survey (NVSS, Condon et al. 1998) at 1.4 GHz, with a lower resolution of 45 arcsec. Sirothia et al. comment that a higher resolution radio image is needed to resolve whether this is a chance association. Higher resolution radio observations of this source are available, as it was observed with

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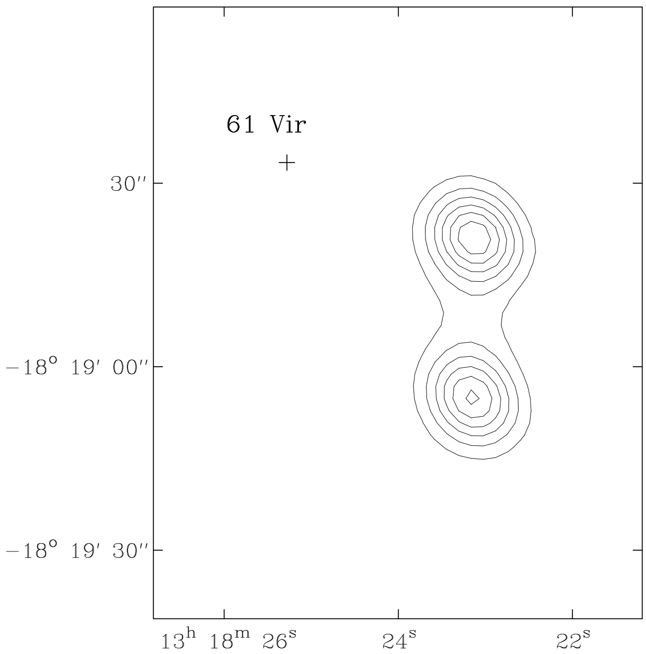

Figure 1. Very Large Array (VLA) image of 61 Vir, at 4.85 GHz, with a resolution of 12.3×10.0 arcsec^2 at a position angle of 46°. The contours are every 1 mJy beam^{-1}. The equatorial coordinates are J2000.

the Very Large Array (VLA) on 1987 February 24, in CD-array at 4.85 GHz (project AC185). We downloaded these observations from the National Radio Astronomy Observatory (NRAO) Science Data Archive, and then calibrated and imaged them using standard procedures in the Astronomical Image Processing System (AIPS) (e.g. Greisen 2003). The observations had a 50 MHz bandwidth centred at 4.85 GHz, with about 1 hour spend observing the source. Figure 1 shows an image of these observations, after primary beam correction. The position of 61 Vir shown in Fig. 1 is for epoch 1987.15, i.e. that of the VLA observations, using the Hipparcos proper motion (van Leeuwen 2007). These observations show a compact (separation about 30 arcsec) radio double source, close but clearly offset from the position of 61 Vir. This double radio source is presumably extragalactic, and therefore a chance association with 61 Vir. The flux density of this source at 4.85 GHz is ≈ 16.5 mJy, which combined with the TGSS 'alternative data release' (Intema et al. 2017) flux density of 229.2 mJy at 150 MHz imply a radio spectral index of α (here defined in the sense that flux density S scales with frequency ν as $S \propto \nu^{-\alpha}$), of ≈ 0.8 which is typical of extragalactic radio sources (e.g. Zhang et al. 2003; Vollmer et al. 2010; de Gasperin et al. 2018).

Murphy et al. (2015) searched for radio emission from 17 exoplanets, using the Murchison Widefield Array (MWA) at 154 MHz. No targets were detected, with 3σ upper limits of between 15.2 and 112.5 mJy. Deeper observations at 150 MHz have been made with the GMRT by Lecavelier Des Etangs et al. (2011); Lecavelier des Etangs et al. (2013) of HD 189733b, HD 209458b and HAT-P-11b. A possible detections at 3.9 ± 1.3 mJy for was reported for HAT-P-11b, as was a source close to HD 189733b with 1.9 ± 0.7 mJy. (At higher frequencies, Lecavelier Des Etangs et al. 2009 report upper limits for HD 189733b from GMRT observations at 240 and 614 MHz.) Lynch et al. (2018) discuss limits from the MWA circular polarisation survey at 200 MHz for declinations below +30° (Lenc et al. 2018), and give 3σ upper limits from 4.0 to 45.0 mJy for 18 exoplanets. In addition, Lynch et al. present targeted GMRT observation at 150 MHz towards one exoplanet, V830 Tau b, which gives a 3σ upper limit of 4.5 mJy. Deeper limits are provided by Low-Frequency Array (LOFAR) observations at 150 MHz, by O'Gorman et al. (2018), with 3σ upper limits between 0.57 and 0.98 mJy for three exoplanets.

3 SOURCE SELECTION

The detectability of cyclotron radio emission from exoplanets is governed by: (a) the magnitude of the emission, which is a function of the system parameters (the stellar properties, orbital separation, and distance to the system), and (b) the gyrofrequency of the emission, which is solely a function of the planetary magnetic field (B_p). Current radio facilities, such as the GMRT, are able to achieve sensitivities of $\sim$ 1 mJy and frequencies as low as 150 MHz. While $\sim$ 1 mJy sensitivities are adequate to detect radio emission from the nearest close-in exoplanets (Jardine & Collier Cameron 2008), the observable minimum cyclotron frequency of 150 MHz restricts the observable planetary magnetic field to $B_\mathrm{p} \gtrsim 50$ G. Radio searches in the past have typically optimised the first of the two factors above, i.e. targeted nearby short-period exoplanets with the highest expected emission, while hoping that $B_\mathrm{p} \gtrsim 50$ G so that the emission is in the observable frequency range to begin with. The non-detections from numerous previous searches, despite the high precisions achieved, raise the question of whether the latter assumption of $B_\mathrm{p} \gtrsim 50$ G is actually applicable for the observed targets.

We aimed to conduct a focused search for potentially radio bright exoplanets selected based on factors that could contribute to their magnetic field strengths. Planetary magnetic fields are thought to be caused predominantly from 'dynamos' in their convective fluidic interiors. The nature of dynamos in planetary interiors is still faced with several open questions (Stevenson 2003). However, some macroscopic dependencies of a planetary magnetic field on the bulk properties can be understood from first order theory and empirical trends observed for solar system planets. The key factors governing the strength of a dynamo in a convective planetary interior are the extent of its electrically conducting region (the volume and conductivity of the convective region) and the planetary rotation. The magnetic moment (μ_p) varies as $\mu_\mathrm{p} \propto \sigma R_\mathrm{p}^3 \Omega_\mathrm{rot}$, where σ is the electrical conductivity of the interior, R_p is the planetary radius, and Ω_rot is the rotation frequency (Durand-Manterola 2009). Magnetic moments of planets in the solar system follow this behaviour, though the conducting material is different between giant planets and terrestrial planets. While metallic hydrogen forms the conducting layer in giant planet interiors, the conducting layer in the Earth is caused by the liquid Fe core.

For a given planet type (rocky or giant) assuming similar rotation periods, larger radii and, hence, more extended conductive interiors may be expected to cause larger magnetic moments as noted above. Thus, the magnetic field strength at the surface of the planet also increases with radius (Lazio 2018). This is evident from the larger magnetic moment and magnetic field in Jupiter compared to Saturn. We, therefore, focused on targets that were giant planets orbiting nearby stars with planetary radii similar to or larger than that of Jupiter (R_J). With this condition on radius, we also considered planets with very different masses and, hence, densities, to span a range in possible metallicities in their interiors. The metallicity in giant exoplanets is known to increase with decreasing mass (e.g., Thorngren et al. 2016; Atreya et al. 2018; Madhusudhan 2019; Welbanks et al. 2019). The metallicities, in turn, could imply different conductivities in the planetary interior.

We observed two targets motivated by the above criteria. The first was the hot Saturn WASP-80b (Triaud et al. 2013) with a mass of 0.54 $M_{\rm J}$ and radius of 1.00 $R_{\rm J}$ (Triaud et al. 2015), i.e. a density of 0.72 g cm^{-3} compared to 1.33 g cm^{-3} for Jupiter. The second target was the hot Jupiter Qatar-1b (Alsubai et al. 2011) with a mass of 1.294 M_J and radius of 1.143 $R_{\rm J}$ (Collins et al. 2017), i.e. a density of 1.15 g cm^{-3}. Both targets have radii comparable to or larger than Jupiter but densities lower than Jupiter, and with very different masses and potential metallicities. WASP-80b is the primary target, as it is at a closer distance than Qatar-1b, $\approx$ 60 pc compared with $\approx$ 190 pc.

4 RESULTS AND CONCLUSIONS

Observations towards Qatar-1b and WASP80b were made with the GMRT, which consists of 30 antennas each 45 m in diameter (see Rao 2002), in 2015 September. These were scheduled to cover a secondary eclipse of the exoplanet[1]. The aim was to look for emission associated with the exoplanet, and if detected, then to look for decrease in emission during the eclipse to confirm the exoplanet emission. The observations were made with a bandwidth of 16.7 MHz, centred at 147.7 MHz, using 256 channels. Both left and right circular polarisations were observed. However, strong interference away from the centre of band – particularly for the Qatar-1b observations – meant than in practice smaller bandwidths of 5.2 and 14.0 MHz, centred at 145.6 and 147.8 MHz were used for Qatar-1b and WASP80b respectively. For each observing run scans on 3C286 and 3C48 were included at the beginning and end the run, for flux density scale calibration, and nearby compact sources were observed every 25 min or so, to monitor the amplitude of phase calibration of the antennas through the run.

The observed u,v-data were processed using standard procedures in AIPS. Interference was flagged by eye, and then several channels near the centre of the band were collapsed together, and these data were tied to the flux scale of Scaife & Heald (2012) from the observations of 3C48 and 3C286. The data were then corrected for antenna-based amplitude and phase variations through the run. The calibration from these collapsed data was then applied to the wider bandwidth using a antenna based bandpass calibration, from the observations of 3C286 and 3C48.

The calibrated u,v-data were imaged using multiple 'facets', which is needed due to the relatively large field-of-view of the observations (the HPBW of the primary beam is about 2 deg at 150 MHz). Both circular polarisations were combined to make Stokes I images. Subsequently several iterations of self-calibration were applied, to correct for residual calibration errors. Phase only self-calibration was applied on decreasing time intervals down to 2 min, with a final self-calibration applied for amplitude and phase on a timescale of 10 min, ensuring that the overall amplitude scaling was preserved.

We do not detect any radio emission from either of our targets The central portions of the final images of Qatar-1b and WASP-80b are shown in Figs 2 and 3. These were made using 'natural' weighting, for maximum sensitivity. The r.m.s. sensitivities are 1.8 and 1.5 mJy beam^{-1} for Qatar-1b and WASP80b respectively. No emission is detected from the positions of the exoplanets. Given the observations span secondary eclipses, any radio emission from the exoplanets would be excluded for some of the observations. The total time on source was 6.3 and 7.7 hr for Qatar-1b and WASP80b respectively, of which 2.0 and 1.1 hr corresponded to the eclipses. Taking these timings into account, the 3σ limits on any radio emission from Qatar-1b and WASP80b are 5.9 and 5.2 mJy, at 145.6 and 147.8 MHz respectively.

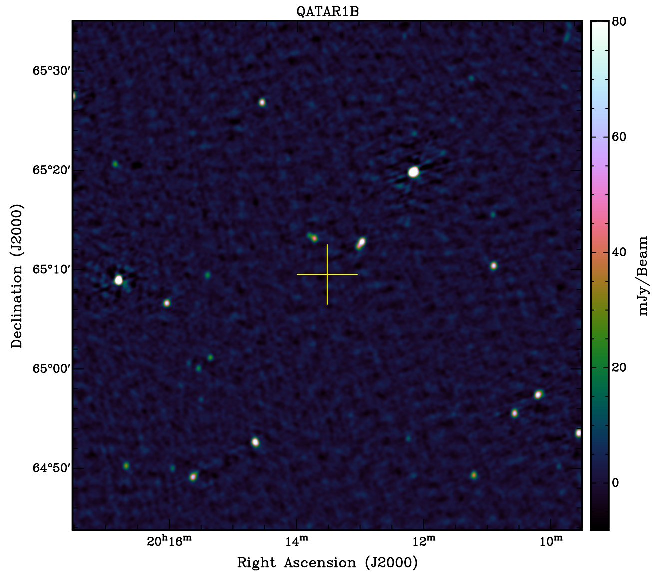

Figure 2. Image of Qatar-1b made with the GMRT at 145.6 MHz. The position of Qatar-1b is indicated by the cross.

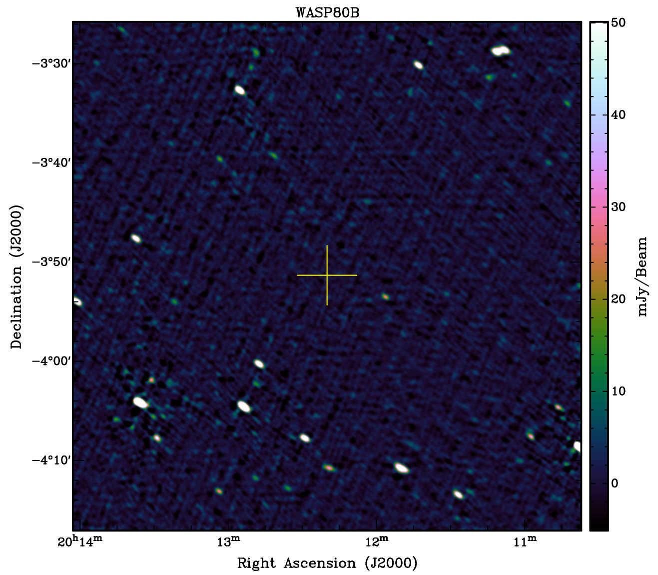

Figure 3. Image of WASP-80b made with the GMRT at 147.8 MHz. The position of WASP-80b is indicated by the crosses.

As discussed in Section 2, Sirothia et al. (2014) noted a radio source in the TGSS close to 61 Vir, which has three planets. However, this radio source is a double source, typical of extragalactic sources, and is significantly offset from the stellar position. We have cross-matched a recent version[2] of an exoplanet catalogue (see Schneider et al. 2011) with the TGSS ADR1 source catalogue from Intema et al. (2017). There are four TGSS sources that closely (< 10 arcsec)

[1] Based on timing from the NASA Exoplanet archive at: `http://exoplanetarchive.ipac.caltech.edu/`.

[2] From `http://exoplanet.eu/catalog/`, with 3221 planetary systems (as of 2020 October 8).

match exoplanets: three are with radio pulsars which have exoplanets (namely PSR B0329+54, PSR B1957+20 and PSR B0943+10), with the other match being with Kepler-652b. The positional offset between the TGSS source and Kepler-652b is ~ 2 arcsec, which is comparable to the error in the TGSS source position. Although a chance association this close is not very probable, it does not seem likely this is a radio exoplanet detection. The TGSS source is quite bright, with a flux density of 69 mJy at 150 MHz, which is much brighter than what might be expected from an exoplanet, especially given Kepler-652b is a Neptune like planet, and is relatively distant (~ 0.42 kpc). The TGSS source is also detected in the Westerbork Northern Sky Survey (WENSS; Rengelink et al. 1997) at 325 MHz with 50 mJy, and at 1.4 GHz in the NVSS survey (Condon et al.) with 27 mJy. These show it has a radio spectral index ($\alpha \approx 0.4$), consistent with an extragalactic radio source, and is considered a chance association with Kepler-652b.

The limits provided here for Qatar-1b and WASP-80b are more sensitive than those available from wide-field radio surveys at similar frequencies (e.g. a median 3σ upper limit of about 25 mJy at 151 MHz from Sirothia et al. 2014). Considering that our chosen targets are giant exoplanets, with potentially higher detectability than smaller planets, our non-detections call for future observations with even higher sensitivities and, where possible, lower frequencies. It is evident from our present, and numerous previous searches, that single eclipse observations may not be adequate for such detections. Future observations may consider co-adding eclipse observations over multiple epochs to improve the sensitivities, as is often pursued to detect low-amplitude spectral features of transiting planets in the near-infrared (e.g., Kreidberg et al. 2014; Stevenson et al. 2014). The increasing number of exoplanets detected around nearby stars may also make future observations of their radio emission more feasible.

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DATA AVAILABILITY

The VLA observations used for Fig. 1 are available in the NRAO Science Data Archive at `https://archive.nrao.edu/`, for Project Code AC185, and GMRT observations used for Figs 2 and 3 are available in the GMRT Online Archive at `https://naps.ncra.tifr.res.in/goa/`, for Proposal Code 28_065.

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